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Hybrid life-cycle assessment for energy consumption and greenhouse gas emissions of a typical biomass gasification power plant in China

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ABSTRACT

Among biomass energy technologies which are treated as the promising way to mitigate critical energy crisis and global climate change, biomass gasification plays a key role given to its gaseous fuels especially syngas for distributed power plant. However, a system analysis for the energy saving and greenhouse gas emissions abatement potentials of gasification system has been directed few attentions. This study presents a system analysis that combines process and input-output analyses of GHG emissions and energy costs throughout the full chain of activities associated with biomass gasification. Incorporating agricultural production, industrial process and wastewater treatment which is always ignored, the energy inputs in life cycle are accounted for the first commercial biomass gasification power plant in China. Results show that the non-renewable energy cost and GHG emission intensity of the biomass gasification system are 0.163 MJ/MJ and 0.137 kg CO_2-eq/MJ respectively, which reaffirm its advantages over coal-fired power plants in clean energy and environmental terms. Compared with other biomass energy processes, gasification performs well as its non-renewable energy cost and CO_2 intensity are in the central ranges of those for all of these technologies. Construction of the plant is an important factor in the process's non-renewable energy consumption, contributing about 44.48% of total energy use. Wastewater treatment is the main contributor to GHG emissions. The biomass gasification and associated wastewater treatment technologies have critical influence on the sustainability and renewability of biomass gasification. The results provide comprehensive analysis for biomass gasification performance and technology improvement potential in regulating biomass development policies for aiming to achieve sustainability globally.

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1. Introduction

As part of its nationally determined contributions to the Paris Agreement, China intends to achieve CO_2 emissions peak in its and to increase the share of non-fossil fuels in its primary energy consumption to 20% by 2030 (NDRC, 2014a, 2014b). Endowed with rich biomass resources, China is striving to develop modern, efficient, clean, and cheap biomass conversion technologies to help meet these goals.

Biomass is typically used in household combustion in last centuries. This old fashion utilization was low-efficiency and had caused severe air pollution (Zhang and Smith, 2007). In the context of ceasing global warming, the first generation of advanced biofuels technologies had been developed over last decades and its production increased steeply between 2005 and 2010 (Sims et al., 2010). The 1 s t-generation biofuels were mainly derived from crops, directly competing for land and water used with food.

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Researches have emphasized on developing second generation biofuels technologies, which mainly use the lingo-cellulose as feedstock. Such feedstocks include by-products of food crops, forest residues, municipal waste and dedicated feedstock. Compared to mature commercial market and supportive polices for 1 s t-generation biofuels, 2nd-generation biofuels remain in deep research stage and partly commercial demonstrations (Mardoyan and Braun, 2014). Studies are dedicated to improve systems efficiency, e.g. pretreatment technology (Maroušek, 2012a), conversion technology (Gao et al., 2012), waste heat utilization technology (Maroušek, 2014), and nutrient management (Maroušek et al., 2014). Simultaneously, some studies emphasized on the importance of policy supports (Mardoyan and Braun, 2014). It is obvious that significant progress is being made in overcoming the economic and technological challenges (Maroušek, 2012a), driving the commercial biomass market development.

As one of the foremost methods of biomass energy utilization, gasification converts biomass into syngas, methanol and hydrogen by means of partial oxidation at high temperatures. Generating electricity from produced syngas is one of low-carbon technologies in the world, being benefit for the electricity structure diversification and environmental impact abatement (Zhou et al., 2012). Biomass gasification technology can be categorized into three types: (1) entrained flow, (2) fixed bed and (3) fluidized bed. However, on the account of very fine particles requirement, entrained-flow bed is rarely applied in dispersed biomass utilization (Zhang et al., 2013). The fixed bed and fluidized bed thus gain more popularity in biomass gasification applications with a capacity from several kW to MW. European countries are leading developers of related technologies. At present, Europe has built 22 well-known gasification plants, including 16 power generation or combined heat and power (CHP) generation ones (Molino et al., 2016), running over 700 MW energy output. And companies in Austria, the United States and Canada have developed gasification plants with high automation levels, complex processes, and scales to several hundred MW (Kwant, 2004). China, a big country embraced with abundant biomass resources, has invested significantly in the development of biomass gasification technologies since the 1980's. Recent studies indicate that approximately 1000 biomass gasification installations are in operation throughout China, with different types and scales (Zhou et al., 2012).

Gasification of biomass is usually considered a form of low-carbon and renewable energy based on conversion processes that convert carbon-neutral agricultural feedstock into syngas for the generation of electricity (Kirkels and Verbong, 2011). Nevertheless, any energy conversion systems need energy during the fabrication of auxiliary inputs, for example the production of metals used to construct equipment that generate electricity from renewable sources (Ju and Chen, 2011) and chemicals that are energy insensitive (Maroušek, 2012b). In China this energy is often provided by fossil fuels—which we refer to as non-renewable energy (NE)—resulting in indirect emissions of GHGs from renewable energy production. With major anticipated growth of renewable industries, moreover, their indirect GHG emissions are likely to grow. However, most studies of biomass gasification focus on technological improvement (Ahmed et al., 2012) and only a few assess its NE cost and GHG emissions. For biomass based SNG supply, Pucker et al. (2012) analyzed the GHG and energy balances of the production of SNG from biomass in the Netherlands. Results showed that fossil primary energy consumption and GHG emissions are reduced compared to natural gas mining and distribution. Luterbacher et al. (2009) discussed the conversion of waste biomass to SNG using a catalytic hydrothermal gasification system, and their results showed that 35.6 MW of thermal electricity fired by SNG derived from a wood feedstock had a GHG emission factor of 0.02 kg CO_2-eq/MJ, indicating relatively good environmental performance. Yang and Chen (2014) proposed a dynamic life-cycle assessment approach to investigate the lifetime environmental performance of a crop-residue gasification project, finding that it had a high net benefit in terms of climate change mitigation. However, Wang et al. (2012) reported the disappointing performance of a Chinese village-level biomass gasification project, judged by NE saving and GHG emissions reduction, due mainly to high costs and low efficiency caused by decentralized construction, technical shortcomings, and low utilization rate of byproducts.

For electricity generation from biomass, Siegl et al. (2011) evaluated the environmental impacts of various biomass conversion technologies in Austria, suggesting that biomass gasification has a relatively high potential for energy saving and emission reduction among conversion technologies. Rafaschieri et al. (1999) conducted a life-cycle assessment of an integrated biomass gasification combined cycle (IBGCC) system in Italy and showed the CO_2 reduction ratio of biomass utilization is about 8.5 to 1 compared with fossil-fueled system. Puy et al. (2010) analyzed the energy consumption and environmental impact of a forest-residue gasification plant in Spain. Results showed that the NE input during the production process was lower than the heat and electricity output. In China, Jia et al. (2004) used Simapro to conduct a life-cycle assessment of a 4 MW BIG/GE-STCC (Gas Engines-Steam Turbine Combined Cycle) power plant. In addition, the environmental impact of a 1 MW husk fluidized bed gasifier (FBG) is discussed using life-cycle assessment in a study by Wang et al. All of these studies concluded that thermal power generation fired by biomass-derived gas is more environmentally-friendly than that fired by coal. It should be noted that research on large-scale biomass gasification power plants is lacking. In addition, there are several limitations to the above studies on China 1) some of the pivotal energy intensity coefficients were adopted from sources researching conditions in other countries (Wang et al., 2012); 2) NE input was not distinguished from total energy input; and 3) system boundaries are different between studies (Yang and Chen, 2014). Regarding the last, biomass production and wastewater treatment of gasification systems are often ignored in previous studies due to lack of data. In these studies, part of the system rather than the whole chain of processes is considered, which affects the accuracy and integrity of the results.

Process based analysis (e.g., LCA) and input-output analysis, are two widely used methods for calculating the energy costs and GHG emissions of target products or services. Process analysis (Yang et al., 2012) attempts to trace each input of a product or service at every stage of the production processes. However, the trace has to be truncated after a few stages as it is ultimately infinite, time-consuming, and liable to form a loop sequence (Bullard et al., 1978). Based on economic input–output tables, input–output analysis (IOA) (Li et al., 2017) can provide a complete modeling of the economy (Leontief, 1970) and is widely employed to overcome truncation errors involved in process analysis (Treloar, 1997). IOA, however, can only quantify sectoral embodied energy, which is unable to distinguish the differences between specific technologies. Therefore, a hybrid approach combining process analysis and IOA, which overcomes the weakness of the two methods, has been developed and applied to calculate the embodied energy and GHG emissions of a given production process (Zhang and Chen, 2010; Yang et al., 2011). More specifically, based on China's input–output table and database (Zhou, 2008), this hybrid method has been widely applied to calculate the NE cost and GHG emissions of, for example, a solar power tower plant and wind farm, the embodied energy of a coal-based power generation system (Wu et al., 2016) and constructed wetland (Shao et al., 2013), the GHG emissions of a biomass-based pyrolysis plant (Yang et al., 2016), and the carbon

emissions of buildings in China (Zhou et al., 2010).

This paper first provides an in-depth account of the NE cost and GHG emissions of a large biomass gasification power plant in China, with a capacity of 20 MW (Peng et al., 2006). The plant converts biomass into syngas used for electricity generation. It takes into account non-renewable material and energy flows and associated GHG emissions over the whole production process, including building works, equipment manufacturing, transportation, operation and maintenance, and wastewater treatment. The accounting boundary includes wastewater treatment processes, as we hypothesized that the non-renewable energy cost and GHG emissions associated with wastewater treatment can not be ignored as most researches did. This study maps NE flows and GHG emissions in detail and helps identify energy-consumption and GHG-intensive components, and thus provides useful information to guide development of a biomass gasification system on a more sustainable trajectory. In addition, the results are compared with traditional coal power plants and other biomass conversion systems, both in China and abroad.

2. Methodology

2.1. Energy indicator

As combustion of fossil fuels is the leading cause of climate change, and with an increasing amount of renewable energy incorporated into the total energy supply system, it is essential to differentiate the consumption of non-renewable and renewable energy. Chen et al. (2010) suggested an indicator of the NE investment in energy delivered (NEIED) to describe the NE cost of a renewable energy-derived system, which is expressed as

$$NEIED = NE/E_{out} \quad (1)$$

where E_{out} is the energy content of the outputs of the studied system. Different ranges of NEIED values have different implications. NEIED <1 stands for a renewable process in which more energy is produced than NE invested, while NEIED >1 illustrates a non-renewable system that consumes more NE than the energy delivered. The smaller NEIED is, therefore, the higher the renewability of the biomass gasification power plant.

During the all processes the embodied nonrenewable energy (NE) consumption can be calculated as:

$$NE = \sum NE_i = \sum (NEI_i) \times MC_i \quad (2)$$

where NE_i denotes the fossil energy used directly and indirectly in the production of the ith input to the gasification system. To calculate the proportion of the primary fossil energy used directly and indirectly in the production or preparation of the ith input, NEI_i is defined as the fossil energy-intensity coefficient of the ith input, and MC_i denotes money cost in the ith input with the unit of 1E+04 USD.

2.2. Greenhouse gas emissions indicator

The net GHG emissions (GHG_{net}) of a product is the sum of two parts. The first is the direct net GHG emissions from the defined system, excepting the CO_2 emission from plants respiration and syngas combustion, because these released CO_2 is originally removed from the contemporary atmosphere by photosynthesis during growth of the biomass. And the second is the indirect net GHG emissions during the fabrication of inputs.

In this study, the direct net GHG emissions include the CH_4 coming from wastewater treatment and rice production process in paddy fields, and N_2O related to nitrogen fertilizer consumption. The indirect net GHG (GHG_{ind}) emissions associated with NE consumption can be calculated as:

$$GHG_{ind} = \sum G_i * MC_i \quad (3)$$

where G_i is defined as the net GHG intensity coefficient of ith input.

The net GHG emission intensity (EI) of the biomass gasification system is thus defined as the net amount of GHG generated per unit of output energy of the system, expressed as:

$$EI = GHG_{net}/E_{out} \quad (4)$$

Larger value of EI means the higher GHG emissions in per unit of output energy of all processes.

2.3. Economic indicator

Net present value (NPV) measures the profit counted by transferring the cash flows at a specified period of time in the future to the flows in terms of present values. Which can be determined as:

$$NPV = \sum_{t=0}^{n} (B_t - C_t - K_t) \Big/ (1+i)^t \quad (5)$$

where B_t and C_t are the benefit and cost in the tth year, K_t represents the investment in the tth year. The *i* indicates the discount rate that reflect the time value.

Internal rate of return (IRR) is the discounted rate at which NPV is equal to zero, which can be calculated by:

$$\sum_{t=0}^{n} (B_t - C_t - K_t)(1+IRR)^{-t} = 0 \quad (6)$$

3. Case description and data source

3.1. Case description

The Jiangsu Lisen Biomass Power Project about 20 MW integrated biomass gasification combined cycle plant is located in Jianhu county, Yancheng city, Jiangsu province, which has abundant biomass resources (both agricultural and forestry wastes). The main data values of the biomass gasification plant are shown in Table 1. A mixed material, consisting of rice husks and straw, are used as feedstock. The total installed capacity of this project is

Table 1
Important data values of the biomass gasification plant in China.

Total output	20 MW
gas engine	36 × 500 kW
steam turbine	4 × 500 kW
Equipment	
gasifier	4
gas engine	36
generator unit	4
waste heat boiler	4
Total investment	5.27E+07 USD
Permanent personnel	183
Construction period	1.5 years
Operating lifetime	20 years
Biomass demand	1.73E+08 kg/yr
Syngas output	3.04E+08 m^3/yr
Auxiliary power rate	9%
Total land area	6.73E+04 m^2
Working time	6000 h/yr

20 MW, which is composed of 36 500-kW gas engine generators and four 500-kW screw expansion generators. Four fluidized-bed gasifiers are used to decompose biomass and provide gas for the engine generator, and four heat-recovery boilers exploit the energy of the exhaust gas from the engine for the screw expansion generator. The total investment in the plant is about 52.86 million USD. Taking one and a half years to construct, the project was designed with an operational lifespan of 20 years. All the cost values are calculated based on at constant 2007 prices in the unit of USD. The unit of CNY is converted into USD in terms of the purchasing power parity (PPP) factor of 3.5 in 2007. Details of the case description and data validation could be found in *Supplementary Materials*.

Six major components of plant performance were studied (as shown in Fig. 2).

(1) Agricultural production;
(2) Transportation;
(3) Building works (combination workshop and office buildings);
(4) Equipment;
(5) Wastewater treatment;
(6) Operation and maintenance.

3.2. Assessment procedures of biomass gasification system

Following this previous research, this study employs the hybrid method to calculate the NE cost and GHG emissions of a biomass gasification plant during an operational lifetime of 20 years. In order to assess the NE cost and GHG emissions of the plant, our research takes all of the non-renewable material and energy inputs directly and indirectly associated with GHG emissions throughout the whole production process into account.

The boundary of this gasification system is shown in Fig. 1. First, a large amount of cement, steel, iron, and other materials were used during the construction phase of the plant. The manufacturing and assembly of equipment (for example, the gasification furnace, combustion engine, generator, storage and decontamination devices, etc.) also consumed energy and generated GHGs. After the plant was completed, biomass in the form of agricultural residues was carried to the power plant (by diesel-burning trucks) and then converted into syngas, which was used to generate electricity through combustion. All of the electricity required during the operation and maintenance of the plant is regarded as auxiliary power and calculated as part of the NE cost and GHG output. Water is also required for gas purification, and wastewater is treated first by mechanical separation using electrical equipment, followed by treatment in an anaerobic pond for bio-separation, while uncontrolled CH_4—which has a large global warming potential—is emitted into the atmosphere. Limited to national statistics, this study mainly considers three GHGs: CO_2, CH_4 and N_2O. Based on the standard of global warming potential over a timescale of 100 years, 1 kg of CH_4 and 1 kg of N_2O are equivalent to 25 kg and 298 kg of CO_2 respectively (Al and Paasche, 2007).

Due to data unavailability, the NE cost and GHG emissions associated with the electricity used during the construction process and auxiliary equipment and labor (which combined account for a negligible proportion of the total) are not taken into account in this study.

3.3. Data sources

All raw data regarding the plant are provided by Nanjing Guolian Electric Power Engineering Design Co., Ltd. (Peng et al., 2006) except inputs in agricultural production which are calculated in Supplementary Materials. In addition, the NE intensity and indirect GHG intensity associated with NE cost and GHG emissions in upstream productions are provided by China's input–output table and database of Chen and Chen (Zhou, 2008). As regard to direct GHG emissions, they are gotten via below calculations.

3.3.1. GHG emissions associated with agricultural practices

For direct CO_2 emissions associated with agricultural practices, the atmospheric CO_2 exchange caused by crop growth is not taken into account, because on an annual basis CO_2 absorption for photosynthesis is about equal to CO_2 emission from crop respiration in farmland ecosystems. CO_2 fluxes are of interest only if they can be related to soil carbon change (Yang, 2011). Tang et al. (2006) estimates the soil organic carbon (SOC) storage in Chinese cropland and forecasts its changing trends under current cropping systems using the DeNitrification and DeComposition (DNDC) model. DNDC model results revealed that the gross SOC storage in croplands in Jiangsu is about 1.33E+11 kg C, and that SOC is lost at a rate of 2.43E+09 kg C/yr. According to *The Second Land National Investigation*, the total cultivated area in Jiangsu in 2008 is over 4.7E+10 m^2. We estimate that the average annual loss of SOC induced by rice planting in Jiangsu is about 1.97E+07 kg/yr.

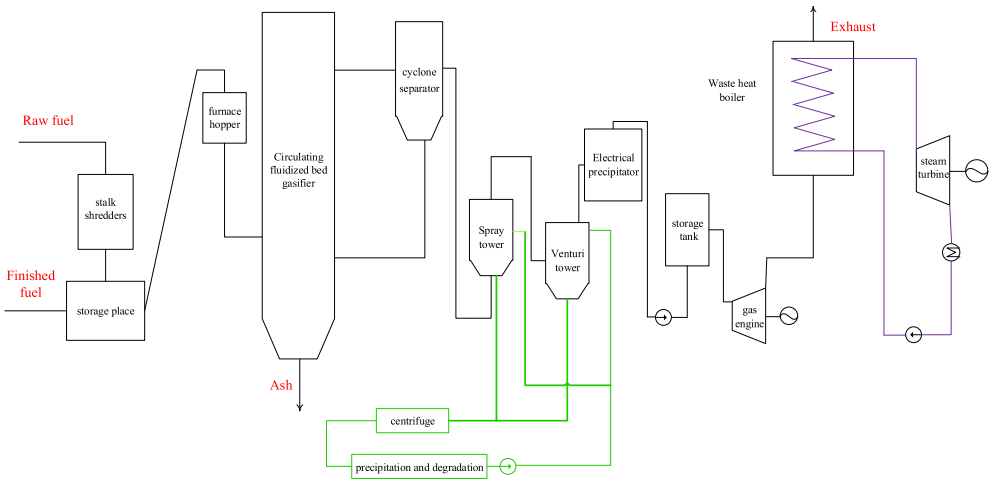

Fig. 1. Diagram of the biomass gasification plant in China.

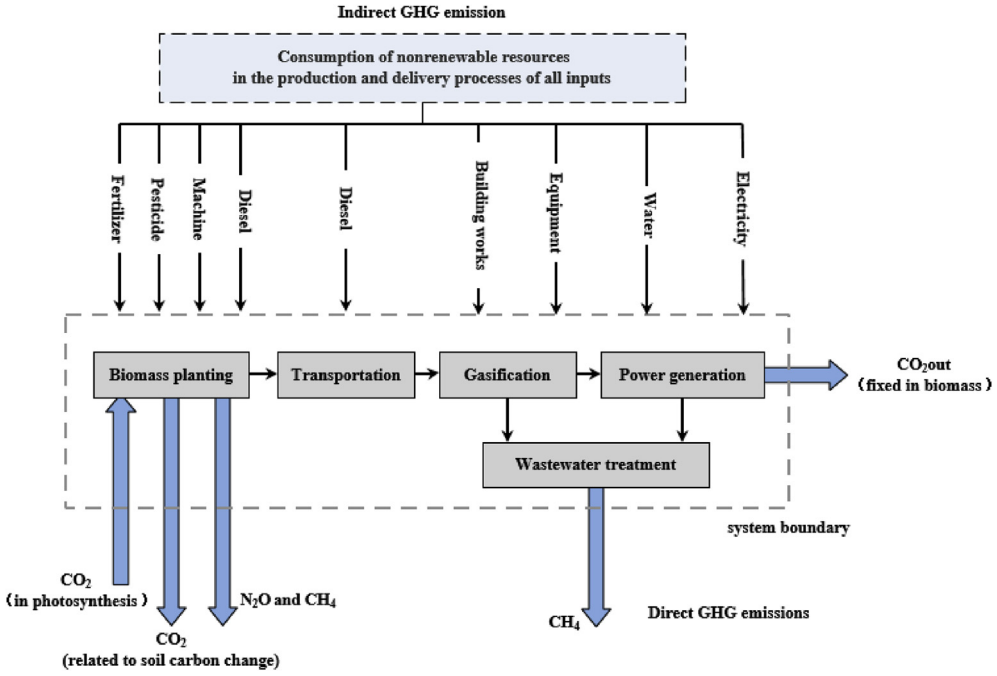

Fig. 2. A schematic drawing of the assessment boundary for a biomass gasification system.

Therefore, the average annual loss of SOC per unit land in Jiangsu can be calculated as 5.13E-02 kg/(m^2·yr). As it is known that the rice planting area is 3.83E+09 m^2, we estimate that the total loss of SOC induced by rice planting during the 20-year lifetime of the plant in this study is about 3.93E+08 kg, which results in 1.44E+09 kg direct CO_2 emissions.

Annual CH_4 emissions from paddy fields have complicated correlations with rice ecosystem type, flooding patterns before and during the cultivation period, number of seasons, temperature of soil, type of rice, etc. The IPCC methodology for estimating CH_4 emissions from rice cultivation involves multiplying daily emission factors by the cultivation period of rice and annual harvested areas. The emission factor defined for a field in which the non-flooded pre-season is 180 days long is regarded as the reference case, the default value of which is 1.30E-04 kg CH_4/(m^2·d). The growing period of medium-maturing rice common in southern China is approximately 130 days. Thus the annual CH_4 emissions from rice cultivation can be calculated as 6.47E+06 kg/yr, and the total CH_4 emissions during the 20-year lifespan in this case can be estimated as 1.29E+08 kg (or 3.23E+09 kg CO_2-eq).

Nitrous oxide (N_2O), as a long-lived GHG, is a participant in photochemical reactions, causing damage to stratospheric ozone which shields life on the earth from solar ultraviolet radiation (Delgado and Mosier, 1996). 58% ~ 72% of N_2O is emitted by natural fields and farm fields (Houghton et al., 2001). The increased input of nitrogen fertilizer into soil is one of the most important reasons for the increase in atmospheric N_2O related to farm fields (IPCC, 1996). The method for calculating direct N_2O based on IPCC protocols involves multiplying fertilizer N inputs by an N_2O emission factor. According to IPCC2006 Guidelines, the default value of the N_2O emission factor in paddy fields is 0.3%, and the nitrogen content of nitrogen fertilizer is counted as 300 g/kg. Furthermore, the amount of N fertilizer should be below 10% before it is multiplied by the emission factor, considering nitrogen volatilization in form of NH_3 or NO_x. In the period of rice cultivation in this case, the nitrogen fertilizer consumption is 9.62E+06 kg/yr. Based on these methods, calculations show the N_2O emissions produced by crop planting is 2.30E+04 kg/yr, while the total N_2O emissions over 20 years is 4.59E+05 kg (or 1.44E+06 kg CO_2-eq).

3.3.2. CH_4 emissions associated with wastewater treatment

Wastewater can be an important source of CH_4 when treated anaerobically. It can also be a source of N_2O and CO_2 emissions, although the latter is not considered because of its biogenic origin (IPCC, 2006). As the nitrogen content of the wastewater produced by the biomass gasification system is very minimal, in this study only CH_4 emissions from wastewater treatment are taken into account. According to the IPCC, CH_4 emissions from wastewater treatment can be calculated as:

$$E_{CH_4} = \sum (TOW_i \cdot EF_i - R_i)$$

where E_{CH_4} represents the CH_4 emissions of wastewater treatment; TOW_i represents the total organically degradable material in wastewater from industry i per year, kg chemical oxygen demand (COD)/yr; EF_i represents the emission factor for industry i, kg CH_4/kg COD; and R_i represents the amount of CH_4 recovered per year, kg CH_4/yr. At the time of this study in 2008, China had not carried out large-scale recycling of CH_4, and as a result the default value of R_i is taken to be zero. The CH_4 emission factor is therefore calculated as:

$$EF = B_0 \cdot MCF$$

where B_0 represents the maximum CH_4 producing capacity, kg CH_4/kg COD, with a default value of 0.25 kg CH_4/kg COD; and MCF stands for the methane correction factor, with a default value of 0.5 based on IPCC and domestic research (Al and Paasche, 2007; IPCC, 2006). The content of COD and the volume of wastewater treated are 6.85E-03 kg/L and 3.20E+05 kg/h, respectively. Based on available data, the annual operational time, and equations (1) and (2), the CH_4 emissions associated with wastewater treatment is 1.64E+06 kg/yr, thus total CH_4 emissions caused by wastewater treatment in this plant over the 20 years is 3.29E+07 kg.

4. Results and discussion

4.1. Non-renewable energy cost and GHG emissions

For the life cycle of the gasification power generation system, the NE cost and GHG emissions are listed in Table 2. The calculated NE requirement of the whole biomass gasification system is 1.28E+09 MJ during its operational lifetime, and the total GHG emissions of the gasification plant over 20 years are calculated as 1.08E+06 t CO_2-eq. The net electricity output is 1.09E+08 kW h per year, with 6000 h available per year while the auxiliary power ratio is 9%. The net total electricity output is 7.86E+09 MJ over the same period. Therefore, the NEIED and GHG emission intensity are calculated to be 0.163 MJ/MJ and 0.137 kg CO_2-eq/MJ respectively, indicating that 0.163 MJ of NE is needed to produce 1 MJ of electricity from the biomass gasification system with 0.137 kg CO_2-eq emission. The lifetime NE consumption of the biomass gasification system in different stages is depicted in Fig. 3. Further analysis of the NE investment in each component shows that the largest contributor to NE consumption is the construction phase, accounting for 44.5% of the total. The transportation of biomass follows, accounting for 14.4% of the total, which is mainly caused by consumption of diesel. Approximately 11.6% of the NE cost is related to biomass production, which can be explained by the considerable input of nitrogen and phosphate fertilizers. And 24.5% results from operation and maintenance, while 3.5% and 2.6% result from loan interest and other expenses (see Fig. 4).

The GHG emissions resulting from the direct and indirect NE consumption of the biomass gasification plant has been evaluated in a way similar to that of the NE analysis (see Table 2). Among them, approximately 1.27E+05 t CO_2-eq is from direct emissions, and therefore the ratio of direct to indirect emissions is approximately 1:8.07. This noteworthy ratio indicates that indirect emissions can be estimated and certainly should not be neglected. As shown in Fig. 3 and 76.4% of total GHG emissions are produced during the wastewater treatment process, due to the high sewage discharge quantities of the plant. And operation and maintenance produces only about 3.5. In addition, due to large inputs of fertilizer, 13.0% of the total GHG emissions are caused by agricultural production, which is mainly related to CH_4 emissions emitted from paddy fields associated fertilizer usage and irrigation, and CO_2 emissions caused by soil organic carbon loss. Because of materials and equipment, the construction phase accounts for 5.48% of the total GHG emissions. Loan interest and transportation cause 0.44% and 1.46% of the total emissions, respectively. Although GHG emissions and NE cost are closely related, the distribution of GHG emissions is vastly different from NE cost, as the spectrum of GHG intensities for the inputs is inconsistent with that of NE intensities.

In China, the NEIED ratio of an average coal-fired thermal power plant is 2.56 MJ/MJ, and the GHG emission coefficient is 0.23 kg CO_2-eq/MJ (Yang and Chen, 2013). It has been found that every MJ of electricity energy output from biomass gasification saves 2.40 MJ

Table 2
NE cost and GHG emissions of the biomass gasification plant during 20 years of operating time.

Item	Component	Cost (1E+04USD)	Sector code	NE intensity (MJ/unit)	GHG intensity (t CO_2-eq/unit)	NE (MJ)	GHG (t CO_2-eq)
Agricultural production	Nitrogen fertilizer	257	40	3.12E+05	3.27E+01	8.01E+07	8.41E+03
	Phosphate fertilizer	22	40	3.12E+05	3.27E+01	6.72E+06	7.05E+02
	Potash fertilizer	49	40	3.12E+05	3.27E+01	1.52E+07	1.60E+03
	Pesticides	50	41	1.70E+05	1.75E+01	8.58E+06	8.87E+02
	Machines	42	71	1.15E+05	1.26E+01	4.85E+06	5.31E+02
	Diesel	63	37	3.07E+05	2.62E+01	1.93E+07	1.64E+03
CO_2 emission							3.79E+04
CH_4 emission							8.51E+04
N_2O emission							3.60E+03
Transportation	Diesel	600	37	3.07E+05	2.62E+01	1.84E+08	1.57E+04
Construction phase							
Thermodynamic system	2 MW gasifier, auxiliary engine and purification system	519	68	1.32E+05	1.43E+01	6.85E+07	7.44E+03
	Gas engine and auxiliary engine	940	81	1.38E+05	1.29E+01	1.15E+08	1.22E+04
	Waste heat utilization system	321	63	1.53E+05	1.68E+01	4.93E+07	5.43E+03
	Hoisting equipment	5	68	1.32E+05	1.43E+01	6.79E+05	7.36E+01
Fuel supply system	Equipment	179	68	1.32E+05	1.43E+01	2.35E+07	2.55E+03
Ash handling system	Equipment	12	68	1.32E+05	1.43E+01	1.55E+06	1.68E+02
Water treatment system	Equipment	252	68	1.32E+05	1.43E+01	3.33E+07	3.62E+03
CH_4 emission							8.22E+05
Water supply system	Equipment	39	67	1.32E+05	1.44E+01	5.19E+06	5.67E+02
Electrical system	Equipment	491	78	1.17E+05	1.25E+01	5.72E+07	6.14E+03
Thermal control system	Equipment	22	84	8.99E+04	9.52E+00	1.93E+06	2.04E+02
Subsidiary production engineering	Equipment in laboratory	29	88	9.83E+04	1.05E+01	2.81E+06	2.99E+02
	Equipment in repair shop	9	88	9.83E+04	1.05E+01	8.43E+05	8.97E+01
Additional services	Site Expropriation fees	146	113	1.75E+04	1.86E+00	2.57E+06	2.72E+02
	Construction management fees	86	115	7.56E+04	8.05E+00	6.46E+06	6.88E+02
	Technical service fees	128	118	4.37E+04	4.65E+00	5.61E+06	5.97E+02
	Production preparation fees	115	117	7.11E+04	7.87E+00	8.18E+06	9.07E+02
	Other fees	9	125	7.94E+04	8.50E+00	7.04E+05	7.53E+01
Construction engineering		711	95	1.40E+05	1.71E+01	9.94E+07	1.22E+04
Installation engineering		612	95	1.40E+05	1.71E+01	8.55E+07	1.05E+04
Operation and maintenance phase							
O&M fees for power plant	O&M fees for power plant	2313	68	1.32E+05	1.43E+01	3.05E+08	3.31E+04
water cost	water cost	66	94	1.18E+05	1.26E+01	7.78E+06	8.31E+02
Loan interest	Loan interest	2907	111	1.52E+04	1.62E+00	4.43E+07	4.71E+03
Other expenses	Other expenses	528	/	6.34E+04	1.17E+08	/	
Total		11524				1.28E+09	1.08E+06

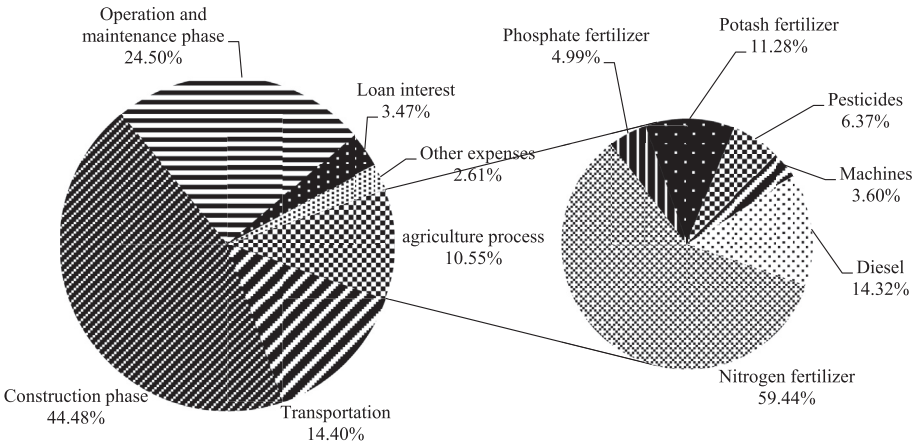

Fig. 3. Contribution to total non-renewable energy cost by stages of the biomass gasification system.

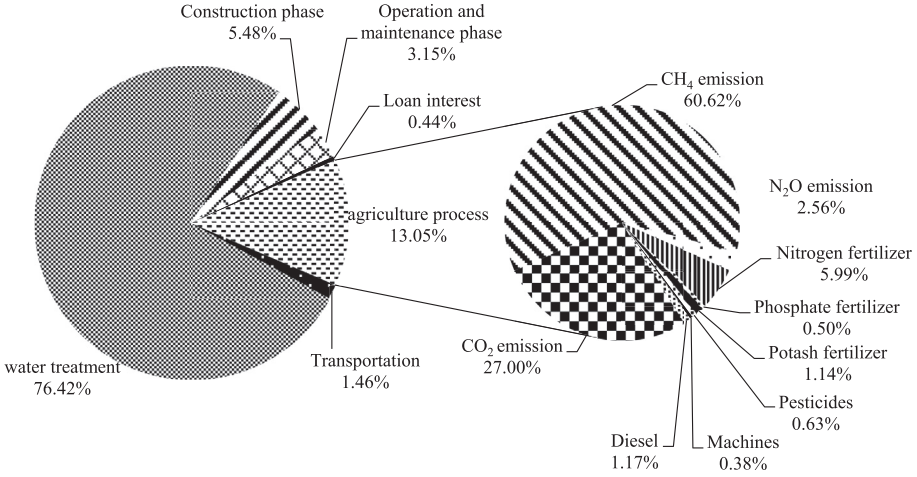

Fig. 4. Contribution to total GHG emissions by stages of the biomass gasification system.

of NE cost, which over 20 years of operations amounts to 1.89E+10 MJ. The GHG emissions of a biomass gasification plant is 40.4% less than those of a comparable coal-fired power plant, although it is shocking small compared with NEIED decrease about 93%, still avoids 7.11E+08 kg CO_2-eq over a 20-year lifetime. Substituting biomass gasification systems for coal-fired power system is plainly beneficial for GHG mitigation.

4.2. Comparison with other biomass utilization technologies and systems

The resulting values are compared with other similar studies as listed in Table 3 These comprise almost all of the biomass thermochemical conversion methods in industrial production. As shown in Table 3, the NEIED spans from 0.09 to 0.89 MJ/MJ (for the biomass gasification systems) and the GHG emission intensity varies from 0.009 to 0.24 kg CO_2-eq/MJ. Papers discussed here study energy plants at which biomass gasification is followed by reformulation of the syngas, or gasification is followed by electricity generation.

In contrast to a biomass gasification-based system for building cooling, heating, and power (BCHP) in China, the NEIED of the biomass gasification power generation system in this study is relatively low, mainly due to different allocation methods and different transportation models that are discussed in the sensitive analysis section in Supplementary Materials. However, the GHG emission intensity of the BCHP system is relatively low compared to the system studied here, reflecting the fact that CH_4 emissions engendered by wastewater treatment and CO_2 emissions caused by loss of soil organic carbon are ignored in the BCHP assessment. As for GHG emissions, the same situation happened in comparing with a biomass gasification power generation system in Austria (Siegl et al., 2011). In addition, the value of NEIED in our study is close to that of a system of forest residue gasification (FRG) in Puy et al. (2010).

Other biomass utilization methods include pyrolysis, direct combustion, integrated utilization, and biofuel. In terms of different biomass utilization patterns, biomass gasification for power generation performs comparatively well. The NEIED and the GHG emission intensity are in the lower range, indicating that biomass gasification is a sustainable and renewable technology in China now. It should also be noted that the energy consumption data for some of the studies in Table 3 are unavailable and/or the NE input was not distinguished from total energy input, which limits comparisons of renewability. Additionally, boundaries of these biomass thermochemical conversion systems are different and some processes are neglected, especially the planting of biomass and treatment of wastewater that drives much of the NE cost and GHG emissions of our assessment.

Table 3
Comparison of different biomass utilization patterns.

Pattern	Application	Year of study	Location	Items	NEIED (MJ/MJ)	GHG emission intensity (kg CO_2-eq/MJ)
Gasification	Electricity generation	2016	China	Biomass gasification plant (this study)	0.163	0.137
		2014	China	Biomass gasification based BCHP system (Wang et al., 2014)	0.803[b,c]	0.016[b,c]
		2011	Austria	Biomass plants for electricity generation by gasification of wood chips (Siegl et al., 2011)	–	0.025[c]
		2010	Spain	Forest residues gasification system (Puy et al., 2010)	0.133[c]	0.242[c]
	Gas supply	2012	China	Village-level biomass gasification project (Wang et al., 2012)	0.89[b,c]	0.17[b,c]
		2014	China	Crop residue gasification project (Yang and Chen, 2014)	–	0.067 −0.105[b,c]
		2012	Netherlands	Substitute natural gas from biomass (bio-SNG) for space heat (Pucker et al., 2012)	0.09 −0.12[c]	0.009–0.016[c]
Pyrolysis	Biochar production	2008	USA	A biomass slow pyrolysis system (Gaunt and Lehmann, 2008)	0.14 −0.50[a]	0.091–0.36[b,c]
	Liquid[b]fuels	2008	Germany	Biomass-to-liquid fuels (Jungbluth N, 2008)	0.69	0.07[c]
		2010	USA	Biomass pyrolysis to produce bio-oil generating system (Fan et al., 2011)	–	0.04[c]
	Poly generation	2015	China	Biomass fixed bed pyrolysis system (Yang et al., 2016)	0.21	0.159[c]
		2015	China	Biomass moving-bed pyrolysis system (Yang et al., 2016)	0.11	0.008
Combustion	Electricity generation	2010	Spain	Biomass-fired power plant (Sebastián et al., 2011)	–	0.30
		2001	USA	15% biomass co-firing power plan (Mann and Spath, 2001)	2.86	0.27[b]
		2003	US[b]	10% willow biomass co-firing power plant (Heller et al., 2004)	2.92	0.25
		2001	USA	5% biomass co-firing power plant (Mann and Spath, 2001)	3.13	0.28[b]
Integrate utilization	Cogeneration	2011	Switzerland	The commercialization technology of SGN from biomass for heat and power (Steubing et al., 2011)	2.09[a]	0.01[c]
		1999	Italy	Biomass IGCC burning power plant (Rafaschieri et al., 1999)	0.08	0.03[c]
	Poly generation	2010	Norway	Biorefinery system producing bioethanol, bioenergy and chemicals (Cherubini and Jungmeier, 2010)	0.28	0.02[c]
Biofuel		2011	China	Corn-ethanol production system (Yang and Chen, 2012, 2013)	1.70	0.39
		2007	USA	Bio-ethanol (Blottnitz and Curran, 2007)	0.02–0.91	0.009–0.602[c]
		2012	Europe, Australia	Bio-diesel (Cherubini et al., 2009; Jørgensen et al., 2012; Nanaki and Koroneos, 2012)	0.02–0.70	0.012–0.091[c]

CO_2 emissions from biomass of the system are taken into consideration during GHG accounting.
[a] The ratio of energy input to energy output of the system while the energy input contains the renewable energy and NE input.
[b] The production of biomass materials is ignored in life cycle assessment of the system.
[c] The treatment and disposal of waste generated by the plant is not taken into account.

4.3. Economic analysis

The expected life time of the biomass gasification power plant is 20 years. At constant 2007 price, the static investment is estimated roughly about 61 million USD. Fig. 5 shows the capital inventory of the plant, in which the construction phase costs largest, accounting for 44.31%. And operation and maintenance phase, loan interest and other expenses take the shares of 22.79%, 27.85% and 5.06% respectively. Furthermore, thermodynamic system (mainly gasification equipment) covers the biggest share in construction phase, which can be explained by expensive and complex biomass gasification equipment in the early state of technological development. Therefore, the result suggests that technology improvement and maturity can effectively influence on economic cost.

In addition, given to the annual utilizing hours of 6000 h for the biomass gasification power plant, the electricity production reaches 1.2E+08 kW h in its whole life cycle. According to the calculation, the static investment cost of this plant is 0.031 USD/kW·h, which is higher than 0.019 USD/kW·h for coal-fired power plant (Zhao and Wang (2014)). It is in accordance with the immature biomass technology development status in China. On the other hand, Zhao and Wang (2014) show that considering the benefits of CO_2

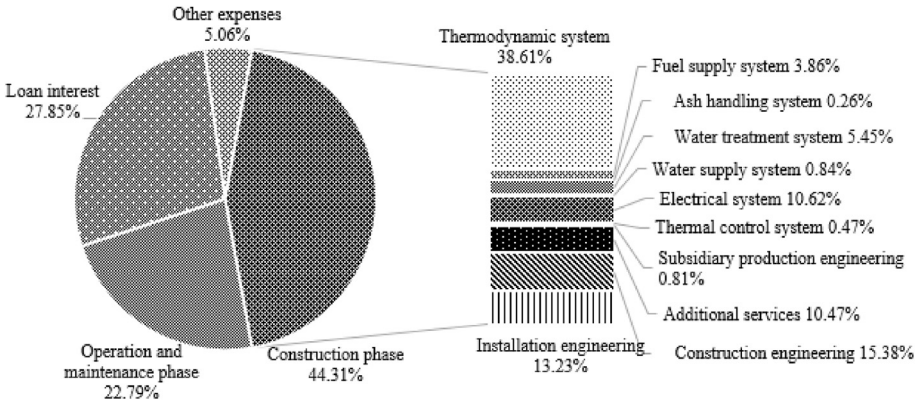

Fig. 5. Capital inventory of the biomass gasification system.

Table 4
Main evaluation indexes in economic for biomass gasification power plant.

Item	Value	unit
Financial internal rate of return (IRR)	12.51	%
Financial net present value (NPV)	2471	1E+04 USD
Investment recovery cycle	8.49	yr
Static investment costs	0.031	USD/kW·h

emission reduction, the total cost of coal-fired power plant is about 0.123 USD/kW·h, which is one order of magnitude higher than that of the gasification power plant in this study. It thus indicates that the biomass gasification power plant has advantages when combining environmental economic benefits.

The main economic evaluation indexes are listed in Table 4. The financial internal rate of return (IRR) of 12.51% is larger than the average value of 8% for Chinese society (The Ministry of Construction, 2006), indicating that the biomass gasification power plant is undertaken in a comparatively desirable way and worthy to invest. Moreover, investment recovery cycle (8.43 years) and NPV also demonstrate that this project is profitable. Therefore, biomass gasification power program has a comparatively promising perspectives both for government and investors.

5. Policy implication

The Paris Agreement on climate change sets up a target aiming to maintain the global temperature below 2 °C with the pre-industrial levels as the reference, and pursue efforts to limit the temperature increase to 1.5 °C. As the largest emitter worldwide, China is now striving to achieve the reduction target. In 2015, China has submitted the Intended Nationally Determined Contributions (INDC), in which China claims that before 2030 it will reach the emissions peak and reduce its CO_2 emissions per unit of GDP by 60%–65% compared to 2005 levels. According to this study, for a biomass gasification power plant, the GHG emissions intensity (EI), defined as the amount of GHG generated per unit of energy output, is 0.137 kg CO_2-eq/MJ. That is to say, 0.093 kg CO_2-eq can be reduced for per MJ electricity from coal-fired power plant is replaced by that from biomass. Moreover, motivated by the "13th Five-Year Plan" for renewable energy development, the installed capacity of biomass based thermal power plants is expected to increase to 15 GW in 2020 (NDRC, 2016a). That means 30 Mt CO_2-eq will be reduced, which equals to 0.56% of the national total in 2005. In 2030, the estimated available amount of biomass will be 5.0E+08 tons of standard coal (CNREC, 2014). If all of those biomass will be used for biomass gasification power plants, the amount of GHG emissions reduced will be equal to 20% of 2005's total. Hence, there is great GHG mitigation potential via promoting biomass gasification power plants.

Furthermore, the neglected water treatment in previous studies is also considered. For decades China's government has noticed that energy production's impact on water and developed wastewater treatment technologies. During the "11th Five-Year Plan" period, the government regulated wastewater treatment industries, and introduced 'Water Pollution Control Action Plan' in 2015 aiming to strengthen the construction of sludge treatment and disposal facilities, fully controlling pollutant emissions. However, these policies didn't focus on wastewater treatment's great carbon emissions, which arrests attention recently in academia (Ma et al., 2015). Also in this study, the wastewater treatment accounts for 76.42% of all GHG emissions, being a major contribution in the biomass gasification processes. The amount of emissions is too large that can not be ignorable. If all potential biomass resource as indicated above is used, the GHG emissions from wastewater treatment are 1168.5 Mt, covering 21.6% of total carbon emissions in 2005. Therefore, it is advisable for government to issue policies on motivating wastewater treatment technologies like combining wastewater treatment with turbine engine or fuel cell so as to use produced methane, felling down GHG emissions to environment.

Over the whole plant lifespan, NE cost attributed to construction and O&M dominates the total NE cost. Moreover, with the future development of biomass gasification, more plants will be constructed with immense materials, services and other inputs. Thus, a great amount of NE cost is caused in both processes. In construction process, thermodynamic system (including all equipment) is key part, covering 41% of total NE consumption in this process. In O&M process, O&M fees for consumable materials is key part, covering about 98% of total NE associated with O&M process. This will be indicative for policy makers in carrying out policies on vigorously developing gasification technologies as well as reducing O&M fees via improving energy efficiency.

In addition, fossil fuel consumption in transportation plays an important role in biomass gasification, with the percentage of 14.40% in total. As calculated previously, the low heating value (LHV) of feedstock is about 14 MJ/kg which is less than half of standard coal's 29.27 MJ/kg. Obviously, the development of biomass-based multi-generation distributed power generation can cut down the energy consumption by shortening the average distance. Shown in Fig. SI1, railway transportation can reduce at least a half of NE cost compared with other transportation ways. That means when all the transportation ways are available, railway is a good choice for fossil energy reduction.

6. Conclusion

Briefly, the most important results are the estimation of a total NE requirement of 0.163 MJ/MJ and a global warming potential of 0.137 kg CO_2-eq/MJ of the plant, reflecting an evident environmental advantage over coal-fired power plants. In addition, the whole results of above economic assessment indicate that the biomass gasification power program is profitable and has promising prospective in developing. The gasification equipment can well fluctuate capital cost in some extent so that it can be seen as a main direction to reduce cost, getting better economic benefits.

In comparison to other thermochemical biomass conversion systems, the subject gasification plant not only has substantial advantages over the majority of similar plants in reducing the NE cost, but also features a GHG emission intensity in the central range of all of biomass-derived systems investigated. It is still necessary to continue investigating and increasing our knowledge of biomass gasification technologies, especially anticipating huge increases in and future growth of deployment of biomass technologies. One priority research area is how to reduce the NE consumption in the construction of relevant equipment and its components. In addition, a well-designed wastewater treatment system is essential for GHG emission reduction. Because the wastewater treatment is confirmed to be an important process with a share of 76.42% in total GHG emissions in this study. To reach these goals quickly and effectively it is vital to have the cooperation and interest of various manufacturers and the Chinese government. This paper will can inform manufacturers of biomass gasification systems, as well as decision makers setting policies for their wider deployment and use.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2018.09.041.

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